

Guide for Determining the Fire Endurance of Concrete Elements

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This Guide for determining the fire resistance of concrete elements is a summary of practical information intended for use by architects, engineers and building officials who must design concrete structures for particular fire resistances or evaluate structures as designed. The Guide contains information for determining the fire endurance of simply supported slabs and beams; continuous beams and slabs; floors and roofs in which restraint to thermal expansion occurs; walls; and reinforced concrete columns. Information is also given for determining the fire endurance of certain concrete members based on heat transmission criteria.

Also included is information on the properties of steel and concrete at high temperatures, temperature distributions within concrete members exposed to fire, and in the Appendix, a reliability-based technique for the calculation of fire endurance requirements.

Keywords: acceptability; beams (supports), columns (supports); compressive strength; concrete slabs, creep properties; heat transfer; fire ratings; fire resistance; fire tests; masonry walls; modulus of elasticity; normalized heat load; prestressed concrete; prestressing steels; reinforced concrete; reinforcing steels; reliability; stress-strain relationship; structural design; temperature distribution; thermal conductivity; thermal diffusivity; thermal expansion; thermal properties; walls.

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This report superseded ACI 216R-81 (Revised 1987). In the 1989 revisions, an appendix has been added outlining a reliability-based technique for the calculation of fire endurance requirements of building elements, along with new Example 7, which demonstrates the use of this technique. References have been added.

Discussion of this report appeared in *Concrete International: Design & Construction*, V. 3, No. 8, Aug. 1981, pp. 106-107

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CHAPTER 1-GENERAL

1.1-Scope

Building codes require that the resistance to fire be considered for most buildings. The type of occupancy, the size of building and its position on the property all affect the fire resistance ratings required of various building elements.

Higher fire resistance ratings often result in lower fire insurance rates, because insurance companies are concerned about fire resistance.

For the most part, fire resistance ratings have been determined by the results of standard fire tests. More recently, rational design methods have been developed which allow the fire resistance to be determined by calculations (Anderberg 1978; Becker and Bresler 1977; Bresler January 1976; Bresler September 1976; Bresler 198.5; Ehm and van Postel 1967; Gustaferro 1973; Gustaferro 1976; Gustaferro and Martin 1977; Iding et al. 1977; Iding and Bresler 1984; Lie and Har-mathy 1972; Nizamuddin and Bresler 1979; Pettersson 1976). The rational design concept makes use of study and research into the properties of materials at high temperatures, the behavior of structures during a fire, and basic structural engineering principles.

This guide illustrates the application of the structural engineering principles and information on properties of materials to determine the fire resistance of concrete construction.

Generally, the information in the Guide is applicable to flat slab floors and rectangular beams. Additional materials and techniques are required for applying the design procedure given in the Guide for structural members that have other geometries.

A technique for the calculation of fire endurance requirements is discussed in the [Appendix](#).

1.2-Definitions and Notation

1.2.1-Definitions

Built-Up Roofing-Roof covering consisting of at least 3-ply 15 lb/100 ft² (0.75 kg/m²) type felt and not having in excess of 1.20 lb/ft² (5.9 kg/m²) of hot-mopped asphalt without gravel surfacing (see Section 7.3 of ASTM E 119-83).

Carbonate Aggregate Concrete-Concrete made with aggregates consisting mainly of calcium or magnesium carbonate, e.g., limestone or dolomite.

Cellular Concrete-A lightweight insulating concrete made by mixing a preformed foam with portland cement slurry and having a dry unit weight of about 30 pcf (480 kg/m³).

Cold-Drawn Steel-Steel used in prestressing wire or strand. Note: Does not include high strength alloy steel bars used for post-tensioning tendons.

Critical Temperature-The temperature of the steel in unrestrained flexural members during fire exposure at which the nominal moment strength of the members is reduced to the applied moment due to service loads.

End Point Criteria-The conditions of acceptance for an ASTM E 119 fire test.

Fire Endurance-A measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance; as applied to elements of buildings it shall be measured by the methods and to the criteria defined in ASTM E 119. (Defined in ASTM E 176)

Fire Resistance-The property of a material or assembly to withstand fire or to give protection from it; as applied to elements of buildings, it is characterized by the ability to confine a fire or to continue to perform a given structural function, or both. (Defined in ASTM E 176)

Fire Resistance Rating (sometimes called *fire rating*, *fire resistance classification* or *hourly rating*)-A legal term defined in building codes, usually based on fire endurance; fire resistance ratings are assigned by building codes for various types of construction and occupancies and are usually given in half-hour increments.

Fire Test-See standard fire test.

Glass Fiber Board-Fibrous glass roof insulation consisting of inorganic glass fibers formed into rigid boards using a binder; the board has a top surface faced with asphalt and kraft paper reinforced with glass fiber.

Gypsum Wallboard Type "X"-A mill-fabricated product made of a gypsum core containing special minerals and encased in a smooth, finished paper on the face side and liner paper on the back.

Heat Transmission End Point-An acceptance criterion of ASTM E 119 limiting the temperature rise of the unexposed surface to an average of 250 F (139 C) or a maximum of 325 (181 C) at any one point.

High Strength Alloy Steel Bars—Bars used for post-tensioning conforming to the requirements of ASTM A 722.

Hot-Rolled Steel—Steel used in reinforcing bars or structural steel members.

Intumescent Mastic—A solvent-base spray-applied coating which reacts to heat at about 300 F (150 C) by foaming to a multicellular structure having 10 to 15 times its initial thickness.

Isotherm—A line drawn on the cross section of a member connecting points of the same temperature.

Lightweight Aggregate Concrete—Concrete made with aggregates of expanded clay, shale, slag, or slate or sintered fly ash, and weighing about 85 to 115 pcf (1360 to 1840 kg/m³).

Mineral Board—A rigid felted thermal insulation board consisting of either felted mineral fiber or cellular beads of expanded aggregate formed into flat rectangular units.

Normalized Heat Load—Total heat absorbed by unit area of the compartment boundaries, such as the walls, floors, and ceiling of a room, during exposure to fire, divided by the thermal absorptivity of the boundaries.

Normal Weight Concrete—Any concrete made with natural aggregates or air-cooled blast furnace slag, cement, and water having a unit weight of about 135 to 155 pcf (2160 to 2480 kg/m³).

Perlite Concrete—A lightweight insulating concrete having a dry unit weight of about 30 pcf (480 kg/m³) made with perlite aggregate concrete. Note: Perlite aggregate is produced from a volcanic rock which, when heated, expands to form a glass-like material of cellular structure.

Restrained Assembly Classification—The classification derived from fire tests of floors, roofs, or beams in accordance with acceptance criteria of Sections 29 and 35 of ASTM E 119-83. Such a classification is considered to be applicable in buildings when (1) the surrounding or supporting structure is capable of resisting the thermal expansion induced by a standard fire (ASTM E 119), or (2) the assembly has structural continuity over supports or has structural continuity with its support.

Sand-Lightweight Concrete—Concrete made with a combination of expanded clay, shale, slag, or slate or sintered fly ash and natural sand. Its unit weight is generally between 105 and 120 pcf (1680 and 1920 kg/m³).

Siliceous Aggregate Concrete—Concretes made with normal weight aggregates consisting mainly of silica or compounds other than calcium or magnesium carbonate.

Spray-Applied Coatings, Sprayed Insulation—See intumescent mastic, sprayed mineral fiber, or vermiculite cementitious material.

Sprayed Mineral Fiber—A blend of refined mineral fibers and inorganic binders. Water is added during the spraying operation, and the untamped unit weight is about 13 pcf (208 kg/m³).

Standard Fire Exposure—The time-temperature relationship defined by ASTM E 119.

Standard Fire Test—The test prescribed by ASTM E 119.

Steel Temperature End Point—The acceptance criterion of ASTM E 119 defining the limiting steel temperatures for unrestrained assembly classifications, i.e., 1100 F (593 C) average or 1300 F (704 C) maximum for structural steel, 1100 F (593 C) average for reinforcing steel, and 800 F (427 C) for

cold-drawn prestressing steel; for restrained classifications of beams spaced more than 4 ft (1.2 m) on centers, these limits must not be exceeded for the first half of the fire endurance period.

Structural End Point—The acceptance criterion of ASTM E 119 which states that the specimen shall sustain the applied load without collapse.

Thermal Absorptivity—A material property defined as $\sqrt{k\rho c}$, where k is thermal conductivity, ρ is density, and c is specific heat. Note: This property characterizes how readily a solid absorbs heat (after a transitional period) from a fluid at different temperature.

Unrestrained Assembly Classification—A classification derived from fire tests of floors, roofs, or beams in accordance with the acceptance criteria of Section 30 of ASTM E 119. Such a classification is considered applicable in buildings when the conditions for a restrained assembly classification are not met.

Vermiculite Cementitious Material—A cementitious mill-mixed material to which water is added to form a mixture suitable for spraying. The mixture has a wet unit weight of about 55 to 60 pcf (880 to 960 kg/m³).

Vermiculite Concrete—A lightweight insulating concrete made with vermiculite aggregate concrete which is a laminated micaceous material produced by expanding the ore at high temperatures. When added to a portland cement slurry the resulting concrete has a dry unit weight of about 30 pcf (480 kg/m³).

1.2.2—Notation

a	= average web thickness of hollow masonry unit (Chapter 3)
a	= depth of equivalent rectangular stress block
a_e	= depth of equivalent rectangular stress block at elevated temperatures
a_{lm}	= minimum measured web thickness
A	= gross cross-sectional area of slab resisting the thrust force
A_{ps}	= area of prestressed reinforcement in tension zone
A_s	= area of nonprestressed tension reinforcement
b	= width of compression face of member
b	= width of joist (Chapter 7)
b	= average web spacing (Chapter 3)
b_E	= width of compression face of column strip at external support
C	= degrees Celsius
d	= distance from extreme compression fiber to centroid of tension reinforcement
d	= minimum length of top reinforcing bars
d'	= distance from extreme compression fiber to centroid of tension reinforcement over the support
E	= modulus of elasticity
f'_c	= specified compressive strength of concrete
f_{ps}	= stress in prestressed reinforcement at nominal strength
f_{pu}	= specified tensile strength of prestressing tendons
f_{py}	= specified yield stress of prestressing tendons
f_y	= specified yield stress of nonprestressed reinforcement
f_{ys}	= specified yield stress of nonprestressed reinforcement at elevated temperatures
F	= degrees Fahrenheit

h	= overall thickness of member
h	= distance between centroidal axis and line of thrust action [Fig. 2.3.2.1(b)]
h	= height of unit (Fig. 3.3.2.2)
h_e	= equivalent thickness
k	= thermal conductivity (at room temperature)
K	= Kelvins
l	= length of unit (Chapter 3)
l	= span length
l	= average face shell thickness (Chapter 3)
l	= length of span of two-way flat plates in direction parallel to that of the reinforcement being determined
l_d	= bar development length
l_m	= minimum measured shell thickness
m	= fraction of weight loss of concrete
M	= design moment
M_n	= nominal moment strength at section
M_{no}	= nominal moment strength at section at elevated temperatures
M_{no}^+	= nominal positive moment strength at section at elevated temperatures
M_{x1}	= moment due to service load at section x_1
R	= universal gas constant
s	= heated perimeter
T	= thrust
t	= time
t_θ	= temperature compensated time
u	= concrete cover over main reinforcing bar or average effective cover
V	= volume of displaced water
w	= applied load (dead + live)
w	= unit weight of concrete
w_{sd}	= service dead load
y_{b1}	= distance from centroidal axis of flexural member to extreme bottom fiber
Z	= Zener-Hollomon parameter
Z'	= A/s
α	= linear coefficient of thermal expansion
β	= constant
Δ	= deflection (Chapter 2)
Δ^H	= activation energy of creep
Δl	= elongation of slab due to temperature
ϵ_i	= creep strain
ϵ_{io}	= creep parameter
θ	= temperature
θ_1	= temperature, F
θ_2	= temperature, C
κ	= thermal diffusivity (at room temperature)
ρ	= density of concrete
ρ_w	= density of water
τ	= fire resistance of concrete wall in natural moist condition
τ_o	= fire resistance of masonry wall in dry condition
ϕ	= volumetric moisture content
ω	= $A_s f_y / b d f'_c$
ω_p	= $A_{ps} f_{pu} / b d f'_c$

1.3-Standard fire tests of building construction and materials

ASTM E 119 specifies the test methods and procedures for determining the fire resistive properties of building components, and is a generally accepted standard for performing fire tests.

1.3.1-Endpoint criteria of ASTM E 119

1.3.1.1-The test assembly must sustain the applied load during the fire endurance test (structural end point).

1.3.1.2-Flame or gases hot enough to ignite cotton waste must not pass through the test assembly (flame passage end point).

1.3.1.3-Transmission of heat through the test assembly shall not increase the temperature of the unexposed surface more than an average of 250 F (139 C) or 325 F (181 C) at any one point (heat transmission end point).

1.3.1.4-There are additional end point criteria for special cases. Those applicable to concrete are as follows:

1.3.1.4.1-Unrestrained concrete structural members: average temperature of the tension steel at any section must not exceed 1100 F (593 C) for reinforcing bars or 800 F (427 C) for cold-drawn prestressing steel.

1.3.1.4.2-Restrained concrete beams more than 4 ft (1.2m) on centers: the temperatures in 1.3.1.4.1 must not be exceeded for classifications of 1 hr or less; for classifications longer than 1 hr, the above temperatures must not be exceeded for first half of the classification period or 1 hr, whichever is longer.

1.3.1.4.3-Restrained concrete beams spaced 4 ft (1.2 m) or less on centers and slabs are not subjected to the steel temperature limitations.

1.3.1.4.4-Walls and partitions must meet the same criteria as in 1.3.1.1, 1.3.1.2, and 1.3.1.3. In addition, they must sustain a hose stream test.

1.4-Application of design principles

In the design of a structural member, the ratio of the load carrying capacity and the anticipated applied loads is often expressed in terms of a “factor of safety.” In designing for fire, the “factor of safety” is contained within the fire resistance rating. Thus for a given situation, a member with a 4 hr rating would have a greater “factor of safety” than one with a 2 hr rating. The introduction to ASTM E 119 states, “When a factor of safety exceeding that inherent in the test conditions is desired, a proportional increase should be made in the specified time-classification period.”

The design methods and examples in this Guide are consistent with the strength (ultimate) design principles of ACI 318. BCGWC the factors of safety in design for fire are included in the resistance ratings, the load factors and strength reduction factor (Sections 9.2 and 9.3) are equal to 1.0 when designing for fire resistance.

CHAPTER 2-FIRE ENDURANCE OF CONCRETE SLABS AND BEAMS

2.1-Simply supported (unrestrained) slabs and beams

2.1.1 Structural behavior -Fig. 2.1.1(a) and (b) illustrate a simply supported reinforced concrete slab. The rocker and roller supports indicate that the ends of the slab are free to rotate and expansion can occur without resistance. The reinforcement consists of straight bars located near the bottom of the slab. If the underside of the slab is exposed to fire, the bottom of the slab will expand more than the top, resulting in a deflection of the slab. The tensile strength of the concrete and steel near the bottom of the slab will decrease as the temperature increases. When the strength of the steel at elevated temperature reduces to that of the stress in the steel, flexural collapse will occur (Gustaferro and Selvaggio 1967).

Fig. 2.1.1(b) illustrates the behavior of a simply supported slab exposed to fire from beneath. If the reinforcement is straight and uniform throughout the length, the nominal moment strength will be constant throughout the length

$$M_n = A_s f_y \left(d - \frac{a}{2} \right) \quad (2-1)$$

where

A_s is the area of the reinforcing steel

f_y is the yield strength of the reinforcing steel

d is the distance from the centroid of the reinforcing steel to the extreme compressive fiber

a is the depth of the equivalent rectangular compressive stress block at ultimate load, and is equal to $A_s f_y / 0.85 f'_c b$ where f'_c is the cylinder compressive strength of the concrete and b is the width of the slab

If the slab is uniformly loaded, the moment diagram will be parabolic with a maximum value at midspan

$$M = \frac{w l^2}{8} \quad (2-2)$$

where w is dead plus live load per unit of length, and l is span length.

It is generally assumed that during a fire the dead and live loads remain constant. However, the material strengths are reduced so that the retained nominal moment strength is

$$M_{n\theta} = A_s f_{y\theta} \left(d - \frac{a_\theta}{2} \right) \quad (2-3)$$

in which θ signifies the effects of elevated temperatures. Note that A_s and d are not affected, but $f_{y\theta}$ is reduced. Similarly a_θ is reduced, but the concrete strength at the top of the slab f'_c is generally not reduced significantly. If, however, the compressive zone of the concrete is heated, an appropriate reduction should be assumed.

Flexural failure can be assumed to occur when $M_{n\theta}$ is reduced to M . From this statement, it can be noted that the fire endurance depends on the load intensity and the strength-temperature characteristics of steel. In turn, the duration of the fire until the "critical" steel temperature is reached depends upon the protection afforded to the reinforcement.

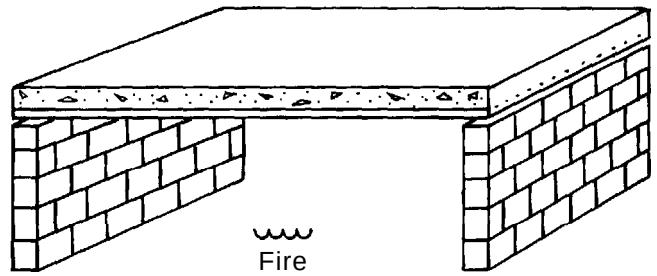


Fig. 2.1.1 (a)-Simply supported reinforced concrete slab subjected to fire from below

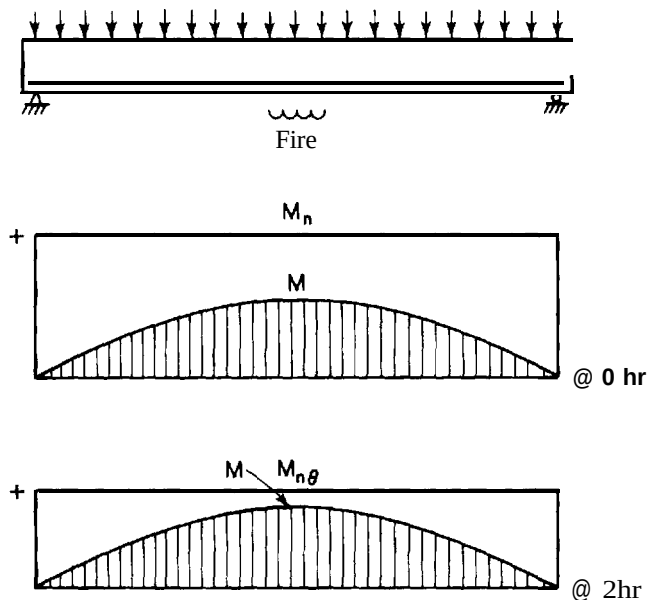


Fig. 2.1.1 (b)-Moment diagrams for simply supported beam or slab before and during fire exposure

Usually the protection consists of the concrete cover, i.e., the thickness of concrete between the fire exposed surface and the reinforcement. In some cases, additional protective layers of insulation or membrane ceilings might be present.

For prestressed concrete the nominal moment strength formulas must be modified by substituting f_{ps} for f_y and A_{ps} for A_s , where f_{ps} is the stress in the prestressing steel at ultimate load, and A_{ps} is the area of the prestressing steel. In lieu of an analysis based on strain compatibility the value of f_{ps} can be assumed to be

$$f_{ps} = f_{pu} \left(1 - \frac{0.5 A_{ps} f_{pu}}{b d f'_c} \right) \quad (2-4)$$

where f_{pu} is the ultimate tensile strength of the prestressing steel.

2.1.2 Estimating structural fire endurance-Fig. 2.1.2.1 shows the fire endurance of simply supported concrete slabs as affected by type of reinforcement (hot-rolled reinforcing bars and cold-drawn wire or strand), type of concrete (carbonate, siliceous, and lightweight aggregate), moment intensity, and the thickness of concrete between the center of the reinforcement and the fire exposed surface (referred to as "u"). If the reinforcement is distributed over the tensile zone

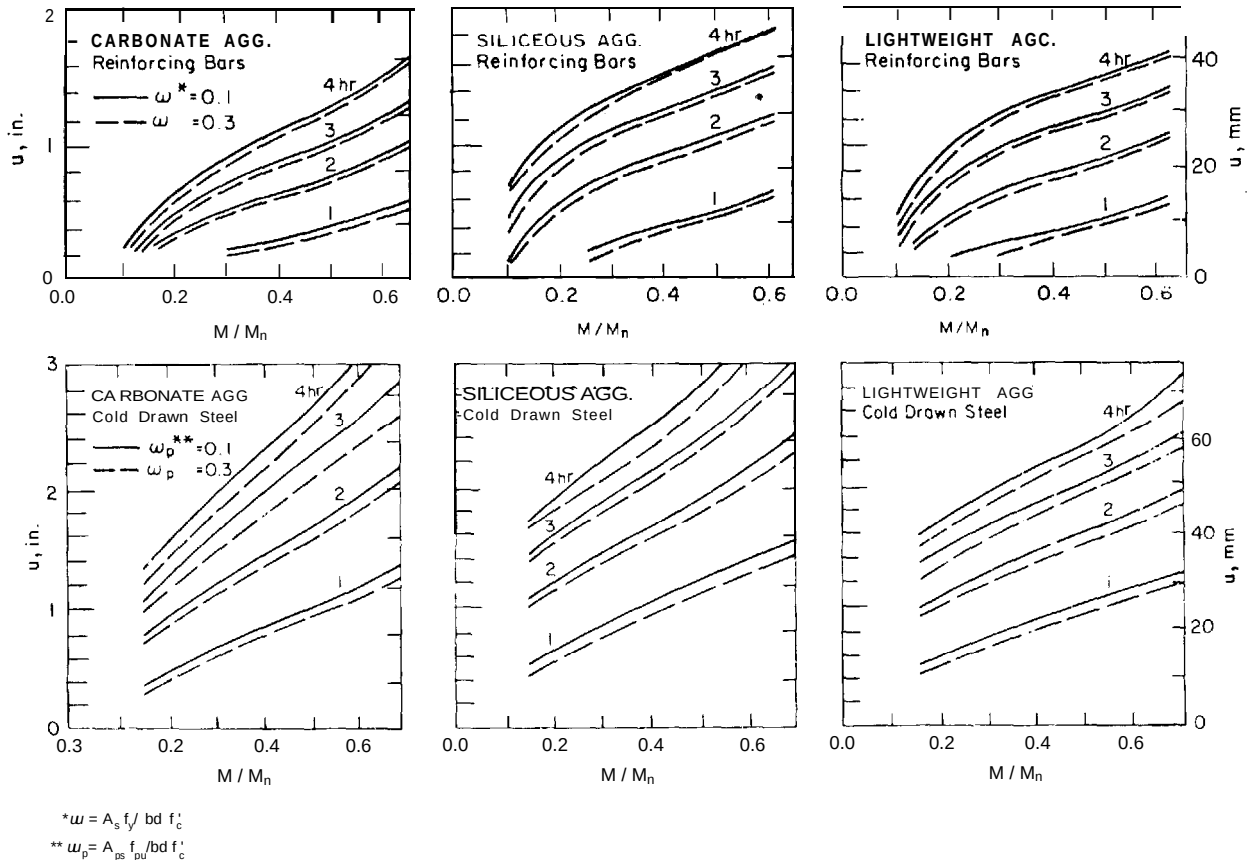


Fig. 2.1.2.1-Fire endurance of concrete slabs as influenced by aggregate type, reinforcing steel type, moment intensity and u (defined in Section 2.1.2)

of the cross section, the value of u is the average of the u distances of the individual bars or strands in the tensile zone. The curves are applicable to the bottom face shells of hollow-core slabs as well as to solid slabs.

The graphs in Fig. 2.1.2.1 can be used to estimate the fire endurance of simply supported concrete beams by using “effective u ” rather than “ u ”. Effective u accounts for beam width by assuming that the u values for corner bars or tendons are reduced by one-half for use in calculating the average u .

Examples 1 and 2 (in Chapter 8) illustrate the use of Fig. 2.1.2.1 in estimating the fire endurance of a slab and a beam. Note: Gustaferro and Martin (1977) present a variety of examples using prestressed concrete. The same principles are applicable to reinforced concrete.

2.2-Continuous beams and slabs

2.2.1 Structural behavior-Structures that are continuous or otherwise statically indeterminate undergo changes in stresses when subjected to fire (Abrams et al. 1976; Ehm and van Postel 1967; Gustaferro 1970; TN0 Institute for Structural Materials and Building Structures Report No. B 1-59-22). Such changes in stress result from temperature gradients within structural members, or changes in strength of structural materials at high temperatures, or both.

Fig. 2.2.1 shows a continuous beam whose underside is exposed to fire. The bottom of the beam becomes hotter than the top and tends to expand more than the top. This differential heating causes the ends of the beam to tend to lift from their supports, thus increasing the reaction at the interior support. This action results in a redistribution of moments, i.e.,

the negative moment at the interior support increases while the positive moments decrease.

During the course of a fire, the negative moment reinforcement (Fig. 2.2.1) remains cooler than the positive moment reinforcement because it is better protected from the fire. Thus, the increase in negative moment can be accommodated. Generally, the redistribution that occurs is sufficient to cause yielding of the negative moment reinforcement. The resulting decrease in positive moment means that the positive moment reinforcement can be heated to a higher temperature before failure will occur. Thus, it is apparent that the fire endurance of a continuous reinforced concrete beam is generally significantly longer than that of a similar simply supported beam loaded to the same moment intensity.

2.2.2 Detailing precautions-It should be noted that the amount of redistribution that occurs is sufficient to cause yielding of the negative moment reinforcement. Since by increasing the amount of negative moment reinforcement, a greater negative moment will be attracted, care must be exercised in designing the member to assure that flexural tension will govern the design. To avoid a compressive failure in the negative moment region, the amount of negative moment reinforcement should be small enough so that ω , i.e., $A_s f_y / b d f'_c$ is less than about 0.30 even after reductions due to temperature in f_y , f'_c , b , and d are taken into account. Furthermore, the negative moment reinforcing bars must be long enough to accommodate the completely redistributed moment and change in the location of inflection points. It is recommended that at least 20 percent of the maximum negative moment reinforcement in the span extend throughout the span

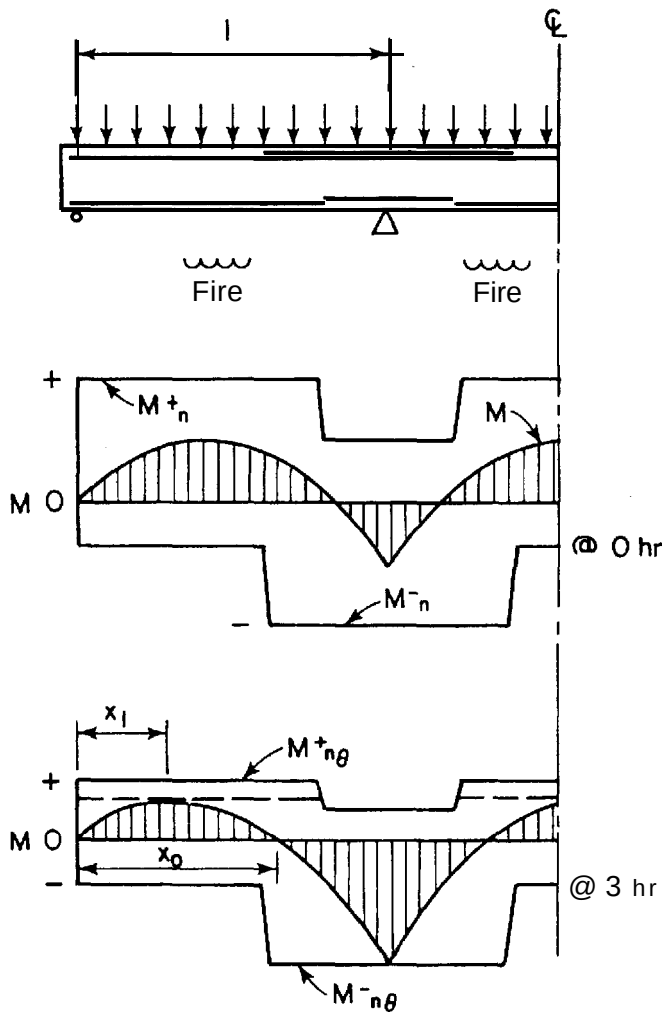


Fig.2.2.1-Moment diagrams for one-half of a continuous three-span beam before and during fire exposure

(FIP /CEB Report on Methods of Assessment of Fire Resistance of Concrete Structural Members 1978).

2.2.3 Estimating structural fire endurance-The charts in Fig. 2.1.2.1 can be used to estimate the fire endurance of continuous beams and slabs. To use the charts, first estimate the negative moment at the supports taking into account the temperatures of the negative moment reinforcement and of the concrete in compressive zone near the supports (see Fig. 2.2.3). Then estimate the maximum positive moment after redistribution. By entering the appropriate chart with the ratio of that positive moment to the initial positive nominal moment strength, the fire endurance for the positive moment region can be estimated. If the resulting fire endurance is considerably different from that originally assumed in estimating the steel and concrete temperatures, a more accurate estimate can be made by trial and error. Usually such refinement is unnecessary.

It is also possible to design the reinforcement in a continuous beam or slab for a particular fire endurance period. Example 3 (in Chapter 8) illustrates this application of Fig. 2.1.2.1. From the lowermost diagram of Fig. 2.2.1, the beam can be expected to collapse when the positive nominal moment strength $M_{n\theta}^+$ is reduced to the value indicated by the

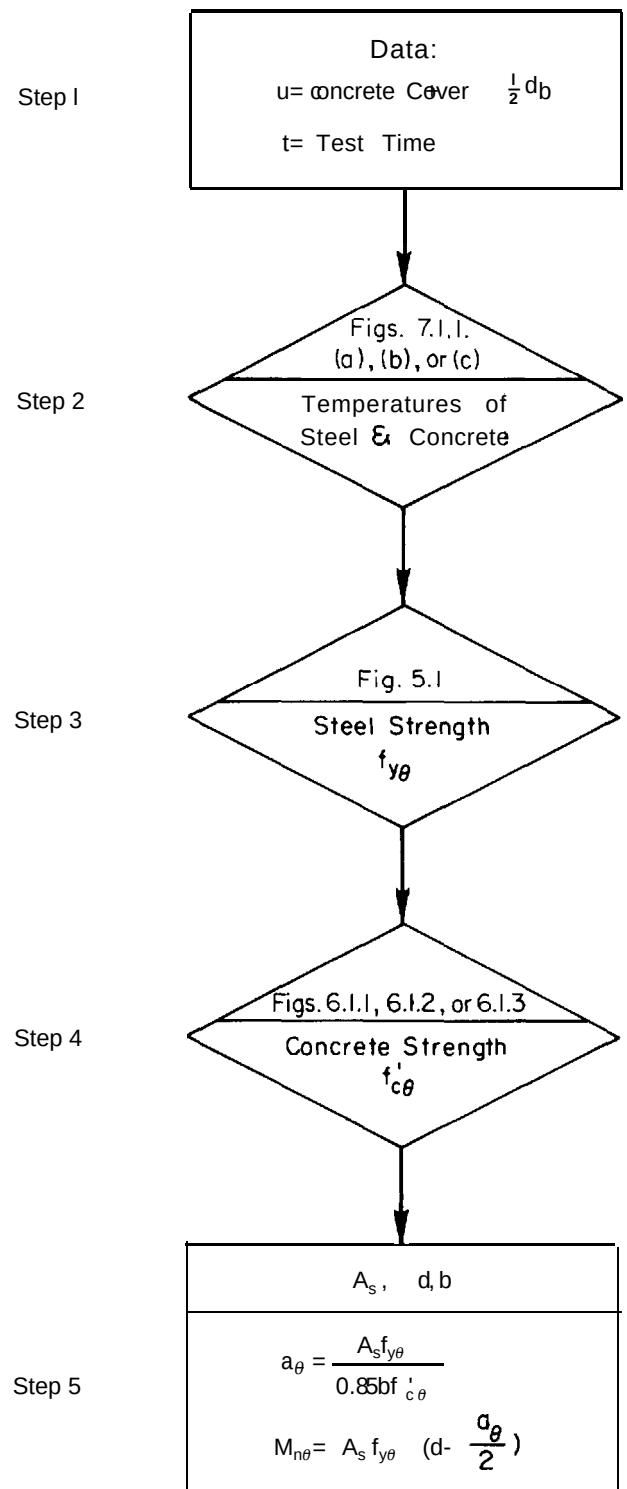


Fig. 2.2.3-Computational procedure for $M_{n\theta}$

dashed horizontal line, i.e., when the applied moment at a point x_1 from the outer support $M_{x1} = M_{n\theta}^+$

For a uniform applied load w

$$M_{x1} = \frac{wlx_1}{2} - \frac{wx_1^2}{2} - \frac{M_{n\theta}^- x_1}{l} = M_{n\theta}^+$$

$$x_1 = \frac{l}{2} \left(\frac{M_{n\theta}^+}{M_{n\theta}^-} - 1 \right)$$

and

$$M_{n0}^- = \frac{wl^2}{2} - wl^2 \sqrt{\frac{2M_{n0}^+}{wl^2}}$$

Also

$$x_o = 2x_1$$

For a symmetrical interior bay

$$x_1 = l/2$$

$$M_{x1} = \frac{wl^2}{8} - M_{n0}^-$$

or

$$M_{n0}^- = \frac{wl^2}{8} - M_{x1}^+$$

2.3-Fire endurance of floors and roofs in which restraint to thermal expansion occurs

2.3.1 Structural behavior—If a fire occurs beneath a small interior portion of a large reinforced concrete slab, the heated portion will tend to expand and push against the surrounding part of the slab. In turn, the unheated part of the slab exerts compressive forces on the heated portion. The compressive force, or thrust, acts near the bottom of the slab when the fire first occurs, but as the fire progresses the line of action of the thrust rises (Selvaggio and Carlson 1967). If the surrounding slab is thick and heavily reinforced, the thrust forces that occur can be quite large, but considerably less than those calculated by use of elastic properties of concrete and steel together with appropriate coefficients of expansion. At high

temperatures, creep and stress relaxation play an important role. Nevertheless, the thrust is generally great enough to increase the fire endurance significantly. In most fire tests of restrained assemblies (Lin and Abrams 1983), the fire endurance is determined by temperature rise of the unexposed surface rather than by structural considerations, even though the steel temperatures often exceed 1500 F (815 C) (Gustaferro 1970; Issen, Gustaferro, and Carlson 1970).

The effects of restraint to thermal expansion can be characterized as shown in Fig. 2.3.1. The thermal thrust acts in a manner similar to an external prestressing force, which, in effect, increases the positive nominal moment strength.

2.3.2 Estimating structural fire endurance—The increase in nominal moment strength is similar to the effect of “fictitious reinforcement” located along the line of action of the thrust (Salse and Gustaferro 1971; Salse and Lin 1976). It can be assumed that the “fictitious reinforcement” has a strength (force) equal to the thrust. By this approach, it is possible to determine the magnitude and location of the required thrust to provide a given fire endurance. The procedure for estimating thrust requirements is: (1) determine temperature distribution at the required fire test duration; (2) determine the retained nominal moment strength for that temperature distribution; (3) if the applied moment M is greater than the retained moment capacity M_{n0} , estimate the midspan deflection at the given fire test time (if M_{n0} is greater than M no thrust is needed); (4) estimate the line of action of the thrust; (5) calculate the magnitude of the required thrust T ; (6) calculate the “thrust parameter” T/AE where A is the gross cross-sectional area of the section resisting the thrust and E is the concrete modulus of elasticity prior to fire exposure (Issen, Gustaferro, and Carlson 1970); (7) calculate Z' defined as $Z' = A/s$ in which s is the “heated perimeter” defined as that portion of the perimeter of the cross section resisting the thrust exposed to fire; (8) enter Fig. 2.3.2 with the appropriate thrust parameter and Z' value and determine the “strain parameter” $\Delta l/l$; (9) calculate Δl by multiplying the strain parameter by the heated length of the member; and (10) determine if the surrounding or supporting structure can support the thrust T with a displacement no greater than Δl . Example 5 (in Chapter 8) illustrates this procedure.

The above explanation is greatly simplified because in reality restraint is quite complex, and can be likened to the behavior of a flexural member subjected to an axial force. Interaction diagrams (Abrams, Gustaferro, and Salse 1971; Gustaferro and Abrams 1971) can be constructed for a given cross section at a particular stage of a fire, e.g., 2 hr of a standard fire exposure.

The guidelines in ASTM E 119 for determining conditions of restraint are useful for preliminary design purposes. Basically, interior bays of multibay floors or roofs can be considered to be restrained and the magnitude and location of the thrust are generally of academic interest only.

2.4-Heat transmission

2.4.1 Single course slab thickness requirements—In addition to structural integrity, ASTM E 119 limits the average temperature rise of the unexposed (top) surface of floors or roofs to 250 F (139 C) during standard fire tests. For concrete slabs, the temperature rise of the top surface is dependent mainly upon the thickness, unit weight, moisture content,

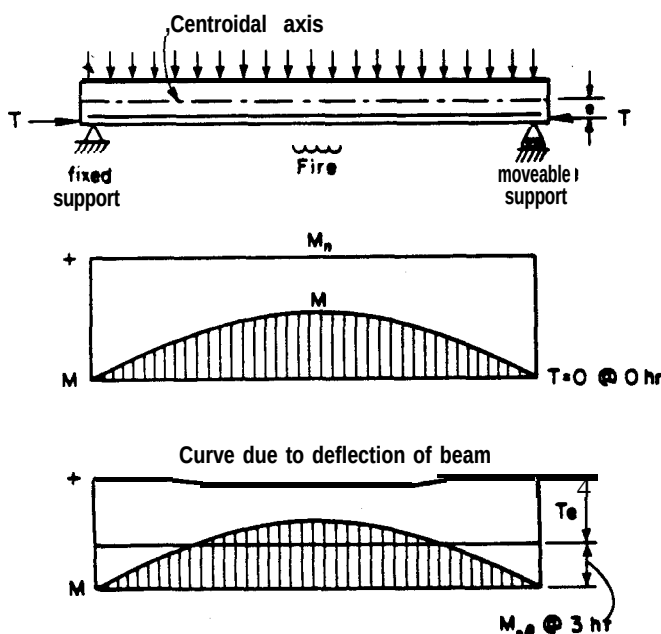


Fig. 2.3.1-Moment diagrams for axially restrained beam during fire exposure. Note that at 3 hr M_{n0} is less than M and effects of axial restraint permit beam to continue to support load (Gustaferro 1970)

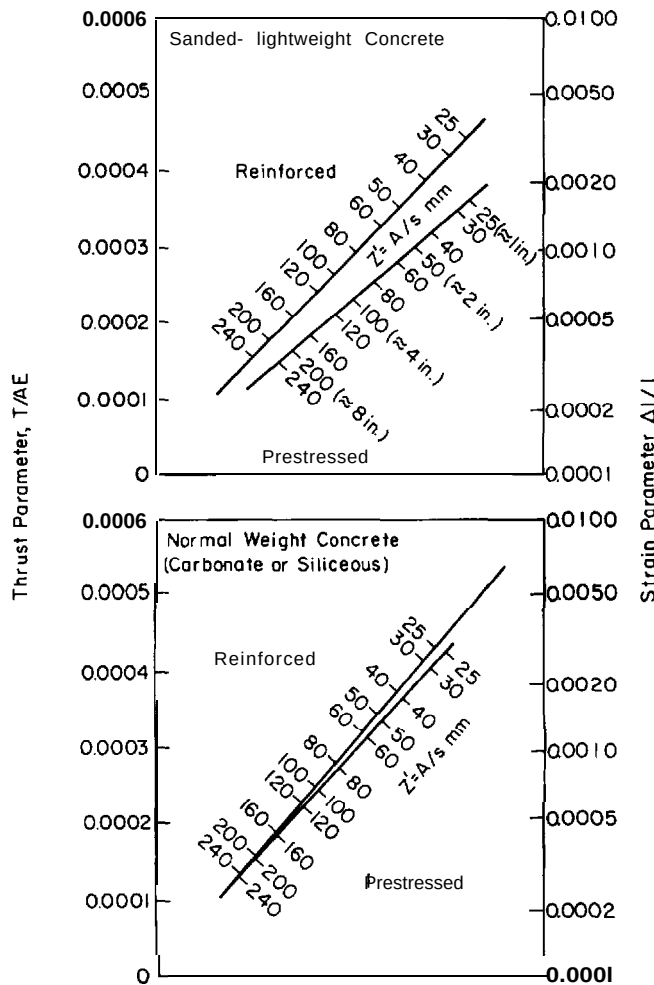


Fig. 2.3.2-Nomogram relating thrust, strain, and Z' ratio (Issen, Gustafsson, and Carlson 1970)

and aggregate type. Other factors that affect temperature rise but to a lesser extent, include air content, aggregate moisture content at the time of mixing, maximum size of aggregate, water-cement ratio, cement content, and slump.

2.4.1.1 Effect of slab thickness and aggregate type-Fig. 2.4.1.1 shows the relationship between slab thickness and fire endurance for structural concretes made with a wide range of aggregates. The curves are for air-entrained concretes fire tested when the concrete was at the standard moisture condition (75 percent relative humidity at mid-depth), made with air-dry aggregates having a nominal maximum size of $3/4$ in. (19 mm). On the graph, lightweight aggregates include expanded clay, shale, slate, and fly ash that make concrete having a unit weight of about 9.5 to 105 pcf (1520 to 1680 kg/m³) without sand replacement. The unit weight of air cooled blast-furnace slag aggregate was found to have little effect on the resulting fire endurance of the normal weight concretes in which it is used.

2.4.1.2 Effect of unit weight-Fire endurance generally increases with a decrease in unit weight. For structural concretes, the influence of aggregate type may overshadow the effect of unit weight. For low density concretes, a relationship exists between unit weight (oven-dry) and fire endurance, as shown in Fig. 2.4.1.2. The curves in Fig. 2.4.1.2 represent average values for concretes made with dry vermiculite or perlite, or with foam (cellular concrete), with or

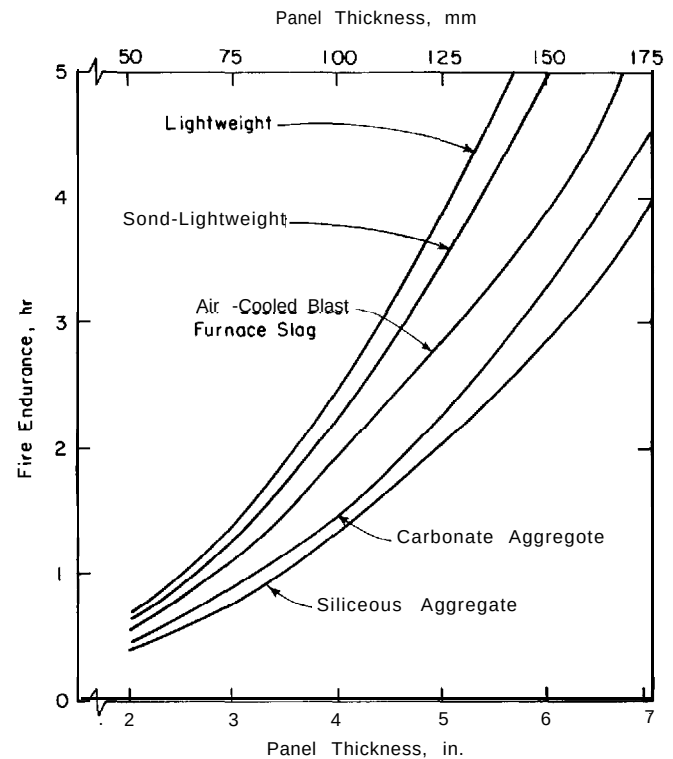


Fig. 2.4.1.1-Effect of slab thickness and aggregate type on fire endurance of concrete slabs. [Based on 250 F (139 C) rise in temperature of unexposed surface]

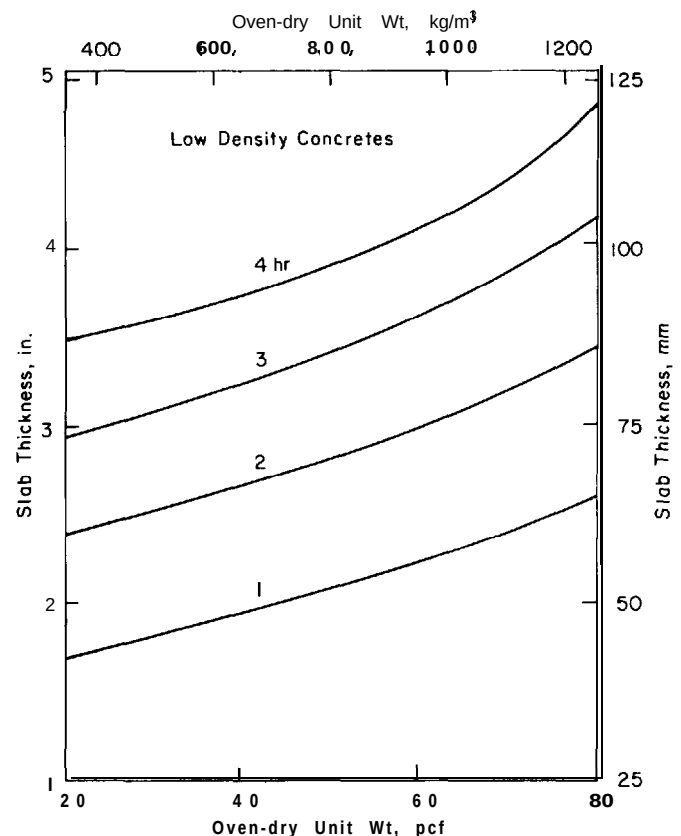


Fig. 2.4.1.2-Effect of dry unit weight and slab thickness on fire endurance of low density concretes. [Based on 250 F (139 C) rise in temperature of unexposed surface]

Table 2.4.2.1(a)-Data on mixes

Symbol	Carb	Sil	LW			
	Carbonate aggregate* concrete	Siliceous aggregate† concrete	Expanded shale aggregate‡ concrete	Vermiculite aggregate concrete	Perlite aggregate concrete	Cellular concrete
Type of mix						
Cement, Type I, lb/yd ³ (kg/m ³)	374(222)	408(242)	446(265)	424(252)	424(252)	673‡(399)
Coarse aggregate, lb/yd ³ (kg/m ³)	1785(1059)	1828(1085)	467(277)	—	—	—
Medium aggregate, lb/yd ³ (kg/m ³)	—	—	248(147)	—	—	—
Fine aggregate, lb/yd ³ (kg/m ³)	—	—	344(204)	—	—	—
Sand, lb/yd ³ (kg/m ³)	1374(815)	1419(842)	1076(638)	—	—	—
Vermiculite aggregate, lb/yd ³ (kg/m ³)	—	—	—	162(96)	—	—
Perlite aggregate, lb/yd ³ (kg/m ³)	—	—	—	—	216(128)	—
Water, lb/yd ³ (kg/m ³)	238*(141)	223** (132)	464††(275)	756(449)	454(269)	424‡‡(252)
Avg air content, percent	6.2	5.8	6.9	—	—	—
Avg wet unit weight, pcf (kg/m ³)	140(2240)	144(2310)	113(1810)	50(800)	41(660)	41(660)
Avg dry unit weight, pcf (kg/m ³)	—	—	—	28(450)	29(465)	30(480)
Avg compressive strength at 28 days, psi (MPa)	4000(28)	4100(28)	3900(27)	270(1.9)	230(1.6)	420(2.9)

*¾ in. (9 mm) maximum size gravel and sand from Elgin, Ill.

†¾ in. (9 mm) maximum size gravel and sand from Eau Claire, Wis.

‡Rotary-kiln produced expanded shale from Ottawa, Ill., and sand from Elgin, Ill.

§Type III cement.

**Based on saturated surface-dry aggregates

††Based on oven dry aggregates

‡‡Includes weight of foam 54 lb/yd³ (32 kg/m³)

without masonry sand (Gustaferro, Abrams, and Litvin 1971).

2.4.1.3 Effect of moisture condition—The moisture content of the concrete at the time of test and the manner in which the concrete is dried affect fire endurance (Abrams and Gustaferro 1968). Generally, a lower moisture content or drying at elevated temperature 120 to 200 F (SO to 9.5 C) reduces the fire endurance. A method is available for adjusting fire endurance of concrete slabs for moisture level and drying environment (Appendix X4, ASTM E 119).

2.4.1.4 Effect of air content—The fire endurance of a concrete slab increases with an increase in air content, particularly for air contents above 10 percent. Also, the improvement is more pronounced for lightweight concrete.

2.4.1.5 Effect of sand replacement in lightweight concrete—As indicated in Fig. 2.4.1.1, replacement of lightweight aggregate fines with sand results in somewhat shorter fire endurance periods.

2.4.1.6 Effect of aggregate moisture—The influence on fire endurance of absorbed moisture in aggregates at the time of mixing is insignificant for normal weight aggregates but may be significant for lightweight aggregates. An increase in aggregate moisture increases the fire endurance. Thus, the fire endurances obtained from Fig. 2.4.1.1 represent minimum values.

2.4.1.7 Effect of water-cement ratio, cement content, and slump—Results of a few fire tests indicate that these factors, per se, within the normal range for structural concretes, have almost no influence on fire endurance.

2.4.1.8 Effect of maximum aggregate size—For normal weight concretes, fire endurance is improved by decreasing the maximum aggregate size.

2.4.2—Two-course floors and roofs

2.4.2.1—Floors or roofs may consist of base slabs of concrete with overlays or undercoatings of either insulating materials or other types of concrete. In addition, roofs generally have built-up roofing. Fig. 2.4.2.2 through 2.4.2.6 show fire endurances of various two-course floors and roofs (Abrams and Gustaferro 1969). Descriptions and symbols of the various concretes and insulating materials referred to in the figures are given in Tables 2.4.2.1(a) and 2.4.2.1(b).

2.4.2.2—Fig. 2.4.2.2 relates to various combinations of normal and lightweight concrete slabs. Note from Fig.

Table 2.4.2.1(b)-Descriptions of materials and mixes

Insulating concrete

Cellular Concrete—A lightweight insulating concrete made by mixing a preformed foam with portland cement slurry and having a dry unit weight of about 30 pcf (480 kg/m³). Foam was preformed in a commercial foam generator.

Vermiculite Concrete—A lightweight insulating concrete made with vermiculite concrete aggregate which is a laminated micaceous material produced by expanding the ore at elevated temperatures. When added to portland cement slurry, a plastic mix was formed having a dry unit weight of about 28 pcf (450 kg/m³).

Perlite Concrete—A lightweight insulating concrete made with perlite concrete aggregate. Perlite aggregate is produced from a volcanic rock which, when heated, expands to form a glass-like material of cellular structure. When mixed with water and portland cement a plastic mix was formed having a dry unit weight of about 29 pcf (460 kg/m³).

Undercoating materials

Vermiculite CM-A proprietary cementitious mill-mixed material to which water is added to form a mixture suitable for spraying. Material was mixed with 1.93 parts of water, by weight, and the mixture had a wet unit weight of 59 pcf (950 kg/m³).

Sprayed Mineral Fiber-A proprietary blend of virgin asbestos fibers, relined mineral fibers and inorganic binders. Water was added during the spraying operation.

Intumescent Mastic-A proprietary solvent-base spray-applied coating which reacts to heat at about 300 F (150C) by foaming to a multicellular structure having 10 to 15 times its initial thickness. The material had a unit weight of 75 pcf (1200 kg/m³) and was used as received.

Roof insulation

Mineral Board, Manufacturer A—A rigid, felted, mineral fiber insulation board; with a flame spread rating not over 20, a fuel contributed rating not over 20, and a smoke developed rating not over 0; conforming to Federal Specification HH-1-00526 b.

Mineral Board, Manufacturer B—Thermal insulation board composed of spherical cellular beads of expanded aggregate and fibers formed into rigid, flat rectangular units with an integral waterproofing treatment.

Glass Fiber Board—Fibrous glass roof insulation consisting of inorganic glass fibers formed into rigid boards using a binder. The board has a top surface faced with asphalt reinforced with glass fiber and kraft.

Miscellaneous

Standard Built-Up Roofing-C is of 3-ply, 15 lb/100 ft² (0.73 kg/m²) felt and not in excess of 1.20 in. (30 mm) of hot mopping asphalt without gravel surfacing (Defined in ASTM E 119).

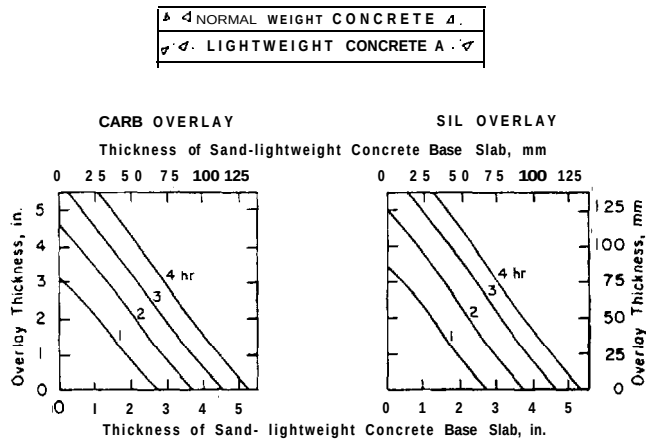


Fig. 2.4.2.2(a) Fire endurance of normal weight concrete overlays on lightweight concrete base slabs

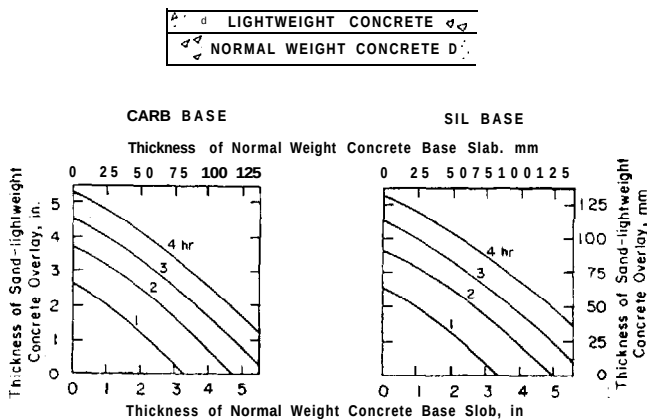


Fig. 2.4.2.2(b) Fire endurance of lightweight concrete overlays on normal weight concrete base slabs

2.4.2.2(a) that a floor consisting of a 3 in. (76 mm) base slab of lightweight concrete with a 2 in. (51 mm) overlay of carbonate aggregate concrete will have a fire endurance of about 3 hr. A method also exists for calculating the fire endurance of floors and roofs of lightweight and normal weight concretes (Lie 1978; Lin and Abrams 1983).

2.4.2.3-Fig. 2.4.2.3 shows fire endurances of concrete floor slabs undercoated with various thicknesses of (a) vermiculite CM, (b) sprayed mineral fiber, and (c) intumescent mastic.

2.4.2.4-Fig. 2.4.2.4 shows fire endurances of roof slabs (without built-up roofing) made of concrete base slabs and insulating concrete overlays. Each of the insulating concretes represented has a dry unit weight of about 30 pcf (480 kg/m³). Standard built-up roofing will add about 10 to 20 min to the fire endurance values.

The graphs in Fig. 2.4.2.4 can be modified to include other types of concrete base slabs or concrete overlays. For example, Fig. 2.4.2.4(a) can be modified as shown in Fig. 2.4.2.4(d) to include an overlay having a dry unit weight of 50 pcf (800 kg/m³). From Fig. 2.4.1.2, thicknesses of 50 pcf (800 kg/m³) material required for 1, 2, 3, and 4 hr can be de-

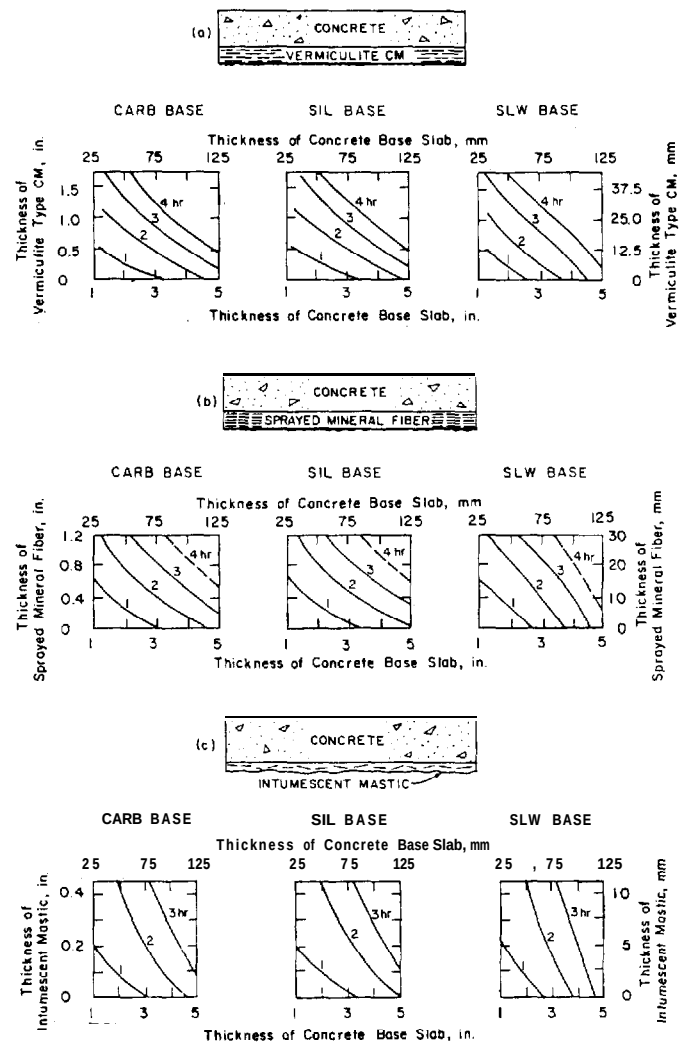


Fig. 2.4.2.3-Fire endurance of concrete slabs undercoated with vermiculite cementitious material, sprayed mineral fiber and intumescent mastic

termined. For 1 hr, a thickness of about 2.1 in. (53 mm) is required. Thus, a curve for 1 hr representing a carbonate aggregate concrete base slab with an overlay of 50 pcf (800 kg/m³) material (shown as a dashed line in Fig. 2.4.2.4(d)) must have an ordinate intercept of 2.1 in. (53 mm), an abscissa intercept of 3.25 in. (83 mm) as on the carbonate base curves in Fig. 2.4.2.4(a), (b), and (c), and the curve must be asymptotic at the abscissa intercept to the solid 1 hr curve in Fig. 2.4.2.4(d). A similar procedure can be used for 2, 3, and 4 hr endurances and also for different concrete base slabs.

2.4.2.5-Fig. 2.4.2.5 shows the fire endurance of concrete roofs with rigid board insulation. Standard built-up roofing is included in the assemblies.

2.4.2.6-Fig. 2.4.2.6 shows the relationship between total slab thickness and fire endurance for three types of terrazzo floors. The "underbed" consists of one part cement and 4 to 5 parts sand with just enough water to permit molding. It can be noted that "monolithic" terrazzo has the same fire endurance as the base slab concrete of the same total thickness. "Bonded" and "sand cushion" terrazzos have somewhat longer fire endurances than Concrete base Slabs of the same total thickness.

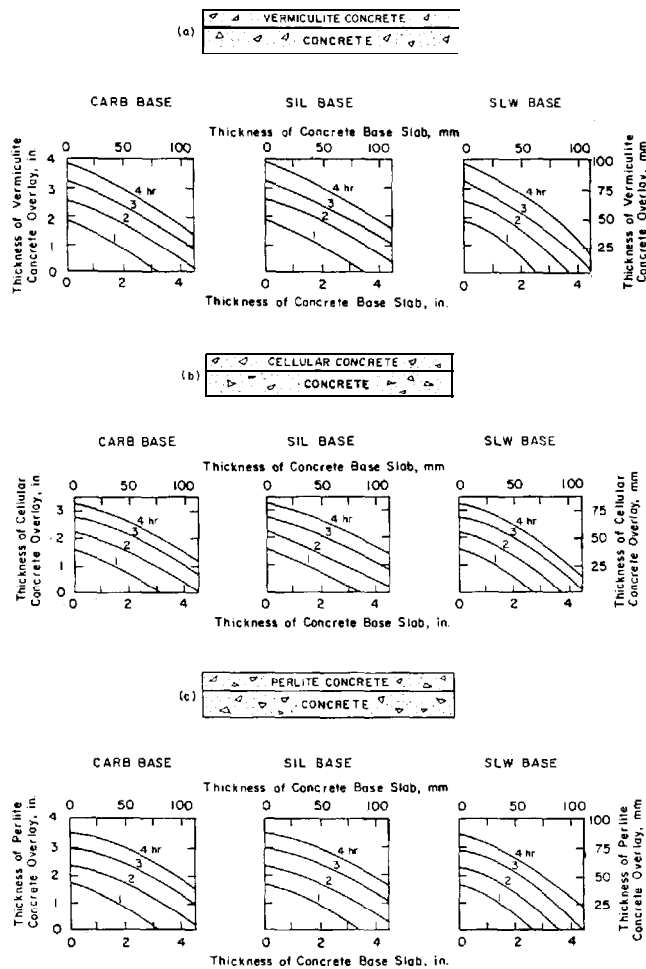


Fig. 2.4.2.4(a), (b), and (c)-Fire resistance of concrete base slabs with overlays of vermiculite, cellular, and perlite concretes

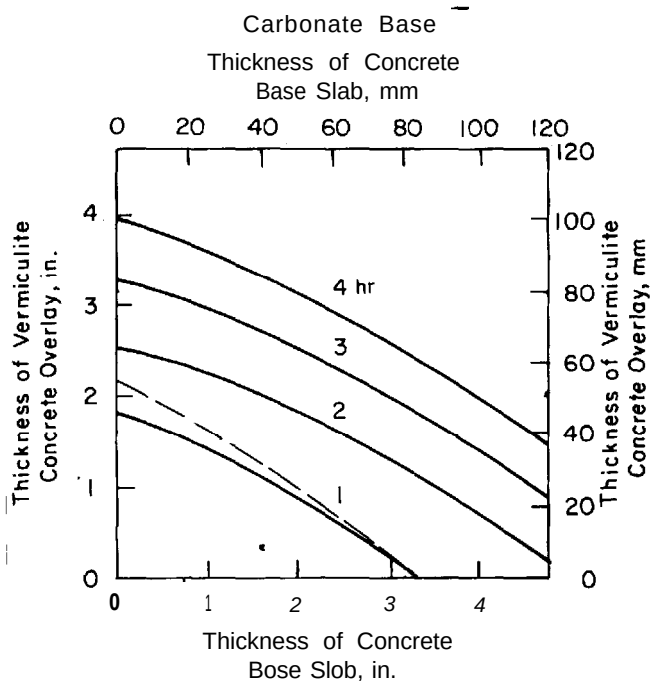


Fig. 2.4.2.4(d)-Dashed line indicates fire endurance of 1 hr for carbonate aggregate concrete base slabs with overlays of concrete having an oven-dry unit weight of 50 pcf (800 kg/m³)

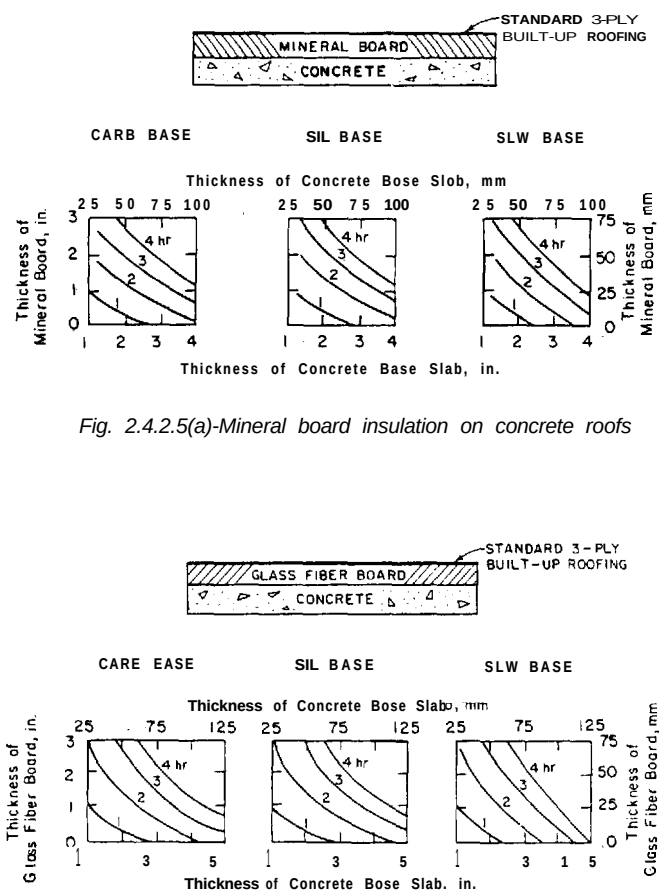


Fig. 2.4.2.5(a)-Mineral board insulation on concrete roofs

Fig. 2.4.2.5(b)-Glass fiber board insulation on concrete roofs

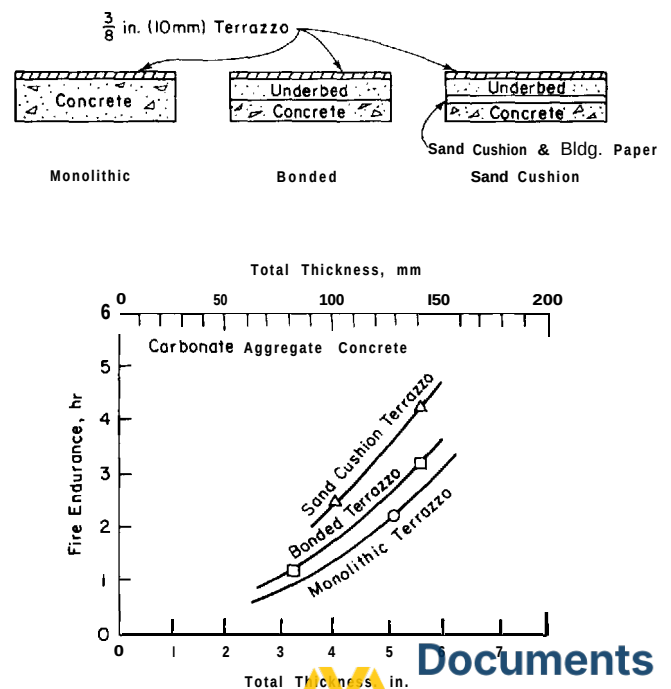


Fig. 2.4.2.6-Fire endurance of terrazzo floors

2.4.3 Other unexposed surface temperature limits-Although ASTM E 119 limits the temperature rise of the unexposed surface to 250 F (139 C), other temperatures may be appropriate for certain conditions. For example, vaults for storage of computer tapes are sometimes designed to keep the temperature within the vault below a certain temperature, such as 200 F (93 C) for a specified duration of a standard fire. To determine the required thickness of a concrete slab (or a two-course floor), it is necessary to have data on the temperature of the unexposed surface during fire tests of such slabs. Fig. 2.4.3 shows the unexposed surface temperatures during fire tests of slabs made of carbonate aggregate concrete. The dashed line in Fig. 2.4.3 indicates, for example, that a slab thickness of about 9.5 in. (241 mm) is required to limit the temperature of the unexposed surface to 200 F (93 C) for a 4 hr fire exposure period.

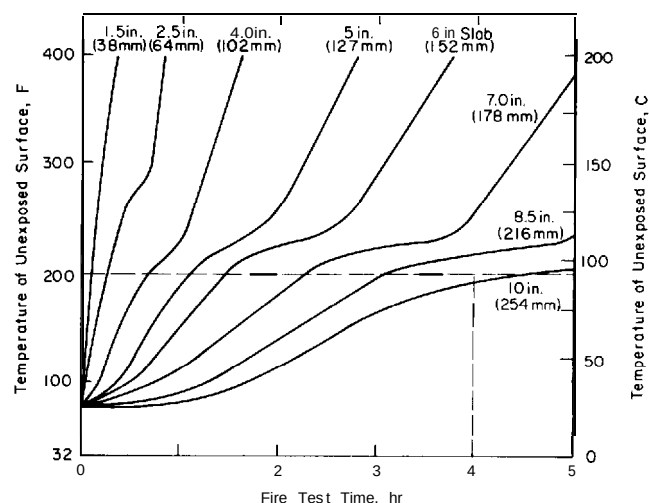


Fig. 2.4.3-Unexposed surface temperatures during fire tests of concrete slabs made with carbonate aggregates (1.5 in. = 38 mm, 2.5 in. = 64 mm, 4 in. = 102 mm, 5 in. = 127 mm, 6 in. = 152 mm, 7 in. = 178 mm, 8.5 in. = 216 mm, 10 in. = 254 mm)

CHAPTER 3—FIRE ENDURANCE OF WALLS

3.1—Scope

3.1.1—In fire tests of walls consisting of plain concrete, reinforced concrete, and concrete masonry units, the fire endurance is generally governed by heat transmission rather than structural consideration assuming that the structural requirement of the building code has been satisfied. For that reason the material in Section 2.4 is basically applicable to this chapter.

3.1.2 *Fire tests of walls*—ASTM E 119 prescribes test methods for bearing walls and for nonbearing walls. The principal difference in the test methods is that the bearing wall is loaded to the working stress contemplated by design and the vertical edges are not restrained whereas the nonbearing wall is not loaded and is restrained on all four edges. An ASTM E 119 hose stream test, which is intended to simulate the cooling and abrading effect of a fireman's hose stream, is a condition of acceptance of fire test results of walls, ASTM E 119 allows the hose stream test to be performed on a duplicate specimen subjected to one-half of that indicated as the resistance period in the fire endurance test, but not for more than 1 hr or performed on the specimen subjected to the fire endurance test. The latter is more severe.

3.1.3 *Bearing and nonbearing walls*—Generally the fire endurance of concrete and concrete masonry walls is determined by heat transmission with the differentiation between bearing and nonbearing walls being based on building code structural requirements.

3.2—Plain and reinforced concrete walls

3.2.1 *Determination of fire endurance*—Plain or reinforced concrete walls are similar to single course slabs. To find their fire endurance the reader is referred to Section 2.4.1 and Fig. 2.4.1.1.

Where other material is placed on one or both sides of a concrete wall, the fire endurance will be increased. See Sections 2.4.2 and 3.3.6.

3.3—Concrete masonry walls

3.3.1 *Solid masonry units—Determination of fire endurance*—The fire endurance of solid concrete masonry unit

walls can be determined as for plain and reinforced concrete walls. See Sections 2.4.1 and 3.2.

3.3.2 *Hollow masonry units—determination of fire endurance*—the fire endurance may be determined by any of the following:

- Fire Test-E 119.
- Interpolation or extrapolation from test results using the “Equivalent Thickness Method”—Section 3.3.2.1.
- Calculation by an “Empirical Method”—Section 3.3.2.2 and Example 6 (in Chapter 8).

The equivalent thickness method has been in use for a number of years. While it may have some shortcomings in a small number of cases, it provides an adequate accuracy for all practical situations.

The empirical method is new. It takes into account variations that may be desirable in evaluating small differences in similar constructions.

3.3.2.1 *Equivalent thickness*—Equivalent thickness is a term intended to quantify the solid contents of the wall. It is determined by dividing the solid volume of a unit by its face area.

3.3.2.1.1 *Underwriter's immersion method*—underwriters Laboratories, Inc. (U.L.) has published a “Procedure for Determining Equivalent Thickness” dated September 1979 which contains details of the procedure and a sketch of the immersion tank. The tank is approximately 8 x 12 in. (200 x 300 mm) and should be at least 24 in. (610 mm) deep. A 0.375 in. (10 mm) weep hole with a 3 in. (76 mm) section of pipe is inserted 17 in. (430 mm) from the bottom of the tank. The unit to be tested is soaked in water for 24 hr. It is then removed, allowed to drain on a screen rack for 1 min then sponged with a clean damp cloth. After 2 min the unit is gently lowered into the container (which has previously been filled with water), and the water from the drain hole is caught in another container. The volume of water displaced is con-

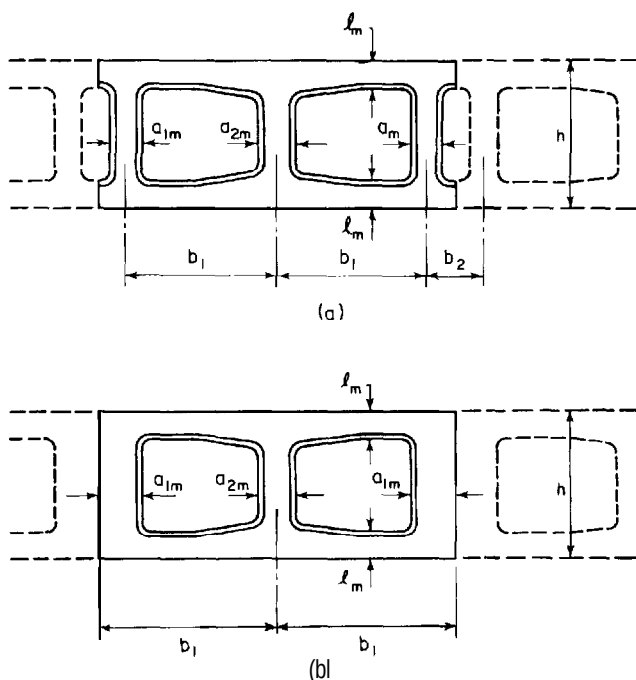


Fig. 3.3.2.2—Hollow masonry units

verted to cubic inches and the equivalent thickness is computed from the formula

$$h_e = \frac{V}{l \times h} \quad (3-1)$$

where

V = volume of displaced water

l = length of unit

h = height of unit

The disadvantage of this method is that lightweight open textured units continue to drain for much longer than 1 min consequently the absolute solid volume of the unit may not be accurately determined.

3.3.2.1.2 ASTM C 140 Immersion Method—In ASTM C 140, Section 10, the net volume of the concrete masonry unit is calculated by weighing dry, wet, and suspended. The net volume (A) replaces V in the U.L. formula to determine the equivalent thickness.

This method has the same disadvantages as the U.L. method.

3.3.2.1.3 Sand or lead shot method—In this method a fairly uniformly graded sand or No. 10 shot is used to fill the cores and recessed ends of the unit (Harmathy and Oracheski 1970). The solid volume of sand or shot is subtracted from the gross volume of the unit. Equivalent thickness is computed by the U.L. formula.

This method is more accurate than the U.L. Immersion Method because fine or coarse texture has little effect on the result and is recommended as the desirable method of determining equivalent thickness.

3.3.2.1.4 Measurement—In the case of hollow units, the thickness can be computed from the block machine manufacturer's drawings.

This method has the advantage of eliminating variations due to aggregate type and gradation as well as compaction of the unit.

The disadvantage is that block molds wear with use. Consequently, block made with old molds do not have exactly the same dimensions as block made with new molds. Block manufactured for a fire test should always be made with new molds. If the equivalent thickness rating is assigned on the basis of fire test of units made with new molds, then the consumer is protected because as block are manufactured the molds wear and the equivalent thickness increases.

3.3.2.1.5 Fire endurance determination—After the equivalent thickness has been determined by one of the above methods, the fire endurance can be estimated from tables or graphs given in the American Insurance Association's "Fire Resistance Ratings" and the Expanded Shale, Clay and Slate Institute's Information Sheet No. 14 on "Fire Resistance of Expanded Shale, Clay and Slate Concrete Masonry." Such tables or graphs were developed from results of numerous fire tests.

3.3.2.2 Empirical method—It must be emphasized that the equivalent thickness is a geometric parameter, and can be used only for interpolation or extrapolation from already available fire test results, within a specific group of concretes of supposedly identical thermal properties. To ascertain whether a particular material indeed belongs to a particular group, one may have to determine its thermal properties. If, however, information on the thermal properties of the material is available, one can use an empirical method for the prediction of the fire resistance, which is more accurate than the technique of interpolation or extrapolation from available fire test data (Allen and Harmathy 1972; Harmathy 1973).

This empirical method can be employed whenever the following information is available:

Material properties (at room temperature):

thermal conductivity k	Btu/h ft F* (W/mK)
thermal diffusivity κ	ft ² /h (m ² /h)

(thermal diffusivity is thermal conductivity divided by product of density and specific heat)

Geometric variables (see Fig. 3.3.2.2):

overall thickness h	ft (m)
average face shell thickness l	ft (m)
average web thickness a	ft (m)
average web spacing b	ft (m)

Volumetric moisture content ϕ ft³/ft³ (m³/m³)

The value a is the average of a_1, a_2 , etc., and b is the average of b_1, b_2 , etc. As the figure shows, the inner cores of the masonry units are generally made with some slope, so that the effective values of l, a_1, a_2 , etc., are not easily obtainable by simple measurements. The following formulas may be used

$$l = 1.1 l_m \quad (3-2)$$

$$a_1 = 1.15 a_m \text{ etc.} \quad (3-3)$$

*In practice k is often expressed in Btu in/h ft²F; to obtain values in Btu/h ft F divide values in Btu in/h ft²F by 12.

where l_m , a_{1m} , etc. are dimensions measured on the side of minimum thickness.

The values of a and b for the shape shown in Fig. 3.3.2.2(a) are obtained as

$$a = \frac{1}{3} (2a_1 + a_2) \quad (3-4)$$

$$b = \frac{1}{3} (2b_1 + b_2) \quad (3-5)$$

and for the shape shown in Fig. 3.3.2.2(b) the average web thickness is expressed as

$$a = \frac{1}{2} (2a_1 + a_2) \quad (3-6)$$

The volumetric moisture content ϕ is obtained from the moisture content expressed as weight fraction m as

$$\phi = m \frac{\rho}{\rho_w} \quad (3-7)$$

where m is usually determined by measuring the weight loss of concrete after sufficiently long heating at 221 F (105 C), ρ is the density of concrete, and ρ_w is the density of water, both densities in pounds per cubic foot (kilograms per cubic meter).

The fire resistance of the masonry wall in dry (moistureless) condition, τ_o , can be calculated from the following expression:

$$\tau_o = - \left(\frac{1}{\frac{a/b}{\tau_{1o}^{1/2}} + \frac{1-a/b}{\tau_{2o}^{1/2}}} \right)^2 \quad (3-8)$$

where

$$\tau_{1o} = C_{14} \left(\frac{k}{h} \right)^{0.55} \left(\frac{h^2}{\kappa} \right)^{1.2} \quad (3-9)$$

$$\tau_{2o} = C_{15} \left(\frac{k}{l} \right)^{0.60} \left(\frac{l^2}{\kappa} \right)^{1.1} \quad (3-10)$$

where

$$C_{14} = \frac{0.205 \text{ ft}^{1.1} \text{ h}^{0.35} \text{ F}^{0.55} / \text{Btu}^{0.55}}{0.0153 \text{ m}^{1.1} \text{ s}^{0.35} \text{ C}^{0.55} / \text{J}^{0.55}}$$

and

$$C_{15} = \frac{0.750 \text{ ft}^{1.2} \text{ h}^{0.5} \text{ F}^{0.6} / \text{Btu}^{0.6}}{0.007 \text{ m}^{1.2} \text{ s}^{0.5} \text{ C}^{0.6} / \text{J}^{0.6}}$$

in the case of solid walls $\tau_o \equiv \tau_{1o}$. The fire resistance of the concrete wall in natural (moist) condition, τ , can finally be obtained from the following formula:

$$\tau = \frac{\tau_o^2 + 4\tau_o(1 + \beta\phi)}{4 + \tau_o} \quad (3-11)$$

where $\beta = 5.5$ for normal weight concretes and $\beta = 8.0$ for lightweight concretes (ASTM E 119).

Example 6 (in Chapter 8) illustrates use of these equations.

3.3.3 Moisture content versus relative humidity—As is stated in Section 2.4.1.3, the amount of moisture in a specimen will affect the fire endurance. In practice, the moisture condition of the specimen is usually expressed in terms of equilibrium relative humidity (in the pores of the concrete). Appendix X4 of ASTM E 119 describes a method for calculating the moisture content from known values of the equilibrium relative humidity.

3.3.4 Effect of aggregate type and aggregate moisture—See Section 2.4.1.

3.3.5 Effect of filling cores—Fire tests show that filling the cores of hollow concrete masonry units with lightweight aggregate increases the fire endurance of the wall. In most cases a 2 or 3 hr rated wall would have its rating increased to 4 hr when the cores are filled with a lightweight aggregate. The aggregate in the cores increases the insulation value of the wall as well as provides additional moisture which absorbs heat during the fire.

3.3.6 Effect of plaster or other material on face of walls—Addition of a layer of plaster or other material to the wall increases the resistance to heat transmission, thus, increasing the fire endurance. The reader is referred to Section 2.4.2 and to UL 618 and the Expanded Shale, Clay and Slate Institute's Information Sheet No. 14 on "Fire Resistance of Expanded Shale, Clay and Slate Concrete Masonry."

CHAPTER 4—REINFORCED CONCRETE COLUMNS

4.1—General

Reinforced concrete columns have performed well during exposure to fire throughout the history of concrete construction.

Columns larger than 12 in. (305 mm) in diameter or 12 in. (305 mm) square are assigned 3 hr and 4 hr fire resistance classifications in most building codes in America.

It is suggested that the information in Table 4.1 be used for designing reinforced concrete columns for exposure to fire. This information is based on the results of a comprehensive series of fire tests on concrete columns (Lie, Lin, Allen, and Abrams 1984). The entire series of the test program consists of 38 full-size concrete columns.

Columns designed in accordance with the requirements of Table 4.1 have been used in concrete buildings for years. These ratings combined with requirements for structural adequacy have given economical column sizes that have performed well.

In the 1970s analytical procedures (Lie and Allen in NRC Technical Papers 378 and 416; Lie and Harmathy 1974) were developed for estimating temperature distributions in concrete columns during exposure to fire and for designing concrete columns for specific fire endurance and loads.

CHAPTER 5—PROPERTIES OF STEEL AT HIGH TEMPERATURES

Evaluating the fire endurance of concrete columns or calculations requires information on certain thermal and mechanical properties of concrete and reinforcing steel over a